GLACIOLOGICAL SURVEY IN THE BARE ICE AREA NEAR THE ALLAN HILLS IN VICTORIA LAND, ANTARCTICA

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Abstract: During the 1978–1979 field season, the third U.S.-Japan joint program entitled "Antarctic search for meteorites" was carried out on the plateau side of the Allan Hills in South Victoria Land. This program included a glaciological study to elucidate the mechanism of accumulation of a large number of meteorites in the bare ice area. In December 1978, a triangulation chain with 20 stations, 15 km in length, was newly established in the Allan Hills bare ice field to investigate the ice flow. Values of elevation and coordinates (X, Y) of all stations are tabulated. The error in elevation of farthest station from the datum point is ± 7 cm, and errors in position of the same station are ± 0.932 m in X coordinate and ± 1.128 m in Y coordinate.

The extensive bare ice area on the ice sheet surface in the vicinity of the Allan Hills is located upstream of the mountain range, and the bare ice fields inland west to the plateau of the East Antarctic ice sheet are located in the neighborhood of a sub-ice bedrock mountain. Therefore, the ice flow coming down towards the Allan Hills or into the Mawson Glacier should be forced to make an upward movement in the neighborhood of the mountains.

1. Introduction

Nine meteorite specimens were found and collected on the bare ice surface west of the Allan Hills in South Victoria Land (Fig. 1) during the 1976–77 summer season by a joint U.S.-Japan meteorite search team (CASSIDY *et al.*, 1977; YANAI, 1978). This new discovery resulted in a revisitation of the site by a new U.S.-Japan joint party during the 1977–78 summer season, and the party was highly successful and collected 303 individual specimens from the same area (YANAI, 1979). During the 1978–79 field season, the third U.S.-Japan joint party utilized small oversnow vehicles to conduct the search over a wider area of bare ice. This field party collected 262 meteorite pieces plus 3 possibles from the same bare ice area as the two previous parties.

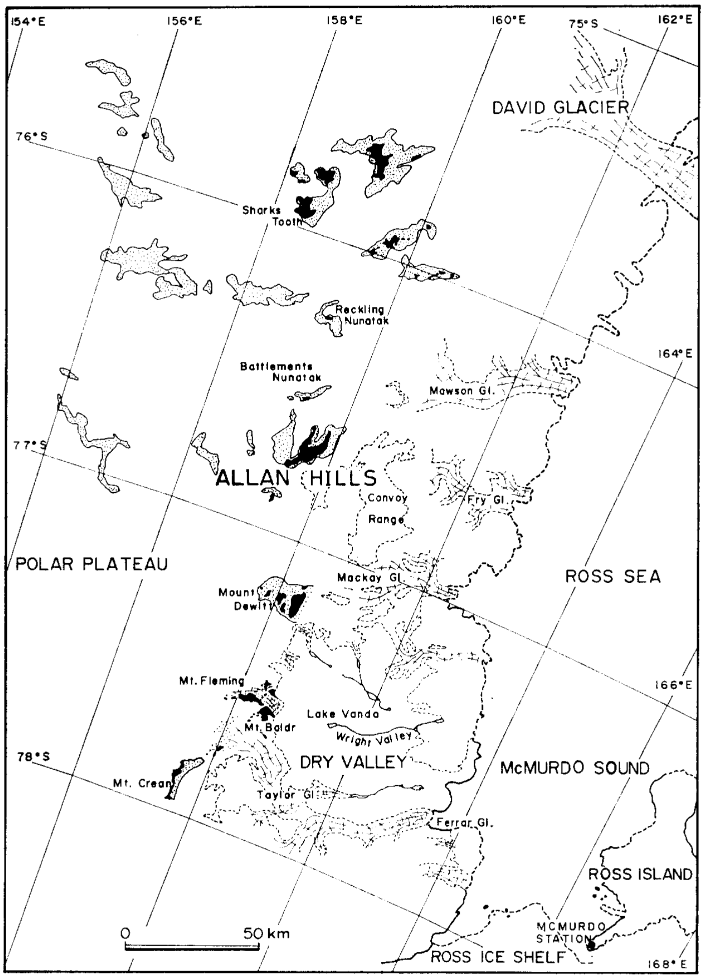

Fig. 1. The location map of the Allan Hills in South Victoria Land, and the bare ice area on the ice sheet (dotted area).

Summarizing the results of these three field works to find and collect meteorites, we may recognize the following: (1) A large number of meteorite pieces collected were found within a small bare ice area of about 50 km^2, west of the Allan Hills. (2) Most of the meteorites collected were found on the bare ice surface and some on the surface of a hard snow layer. (3) Meteorites were also found among basalt, tillite, coal and sandstone of localized morainal deposits. (4) Although the ice sheet surface in the Allan Hills field exhibits a step-like topography with the elevation increasing westward, most of the meteorite pieces collected were found at the bottom of the valley (Fig. 2).

The Allan Hills region with its limited ice field area, which has large concentrations of meteorites as mentioned above and is in close proximity to McMurdo Station (230 km), was selected as the site for a glaciological survey during the

1978–79 field season to clarify the mechanism of accumulation of a large number of meteorites in the bare ice area. This paper describes the method of survey, the reduction of observed data and the characteristic features of the ice sheet in the Allan Hills area.

In December 1978, a triangulation chain with 20 stations, 15 km in length, was established in the Allan Hills bare ice field to investigate the ice flow. Although the triangulation chain survey is a laborious task, it has two advantages in ice sheet flow research. The first is that an observational error at an individual triangle of a chain can be checked and corrected *in situ* so that the total error accumulated throughout the survey can be controlled within a much smaller value than is possible in a traverse survey. The second is that both the velocity of the ice flow and the distribution of surface strain rates of the ice sheet are obtainable by this method.

2. Installation of Triangulation Chain

The triangulation chain as shown in Fig. 2 extends for about 15 km between the

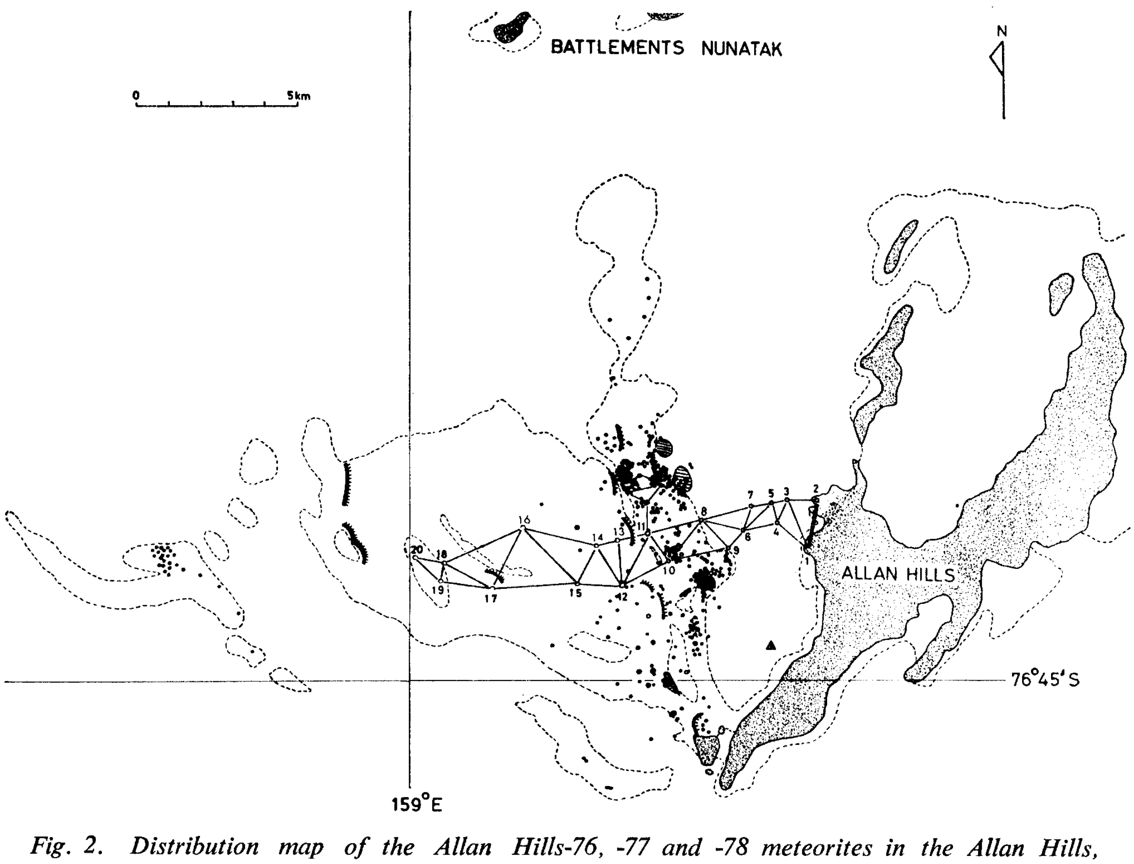

Fig. 2. Distribution map of the Allan Hills-76, -77 and -78 meteorites in the Allan Hills, South Victoria Land, and configuration of the triangulation chain. The number attached to each station of the triangulation chain is the station number, and the solid circles show the sites of meteorite finds.

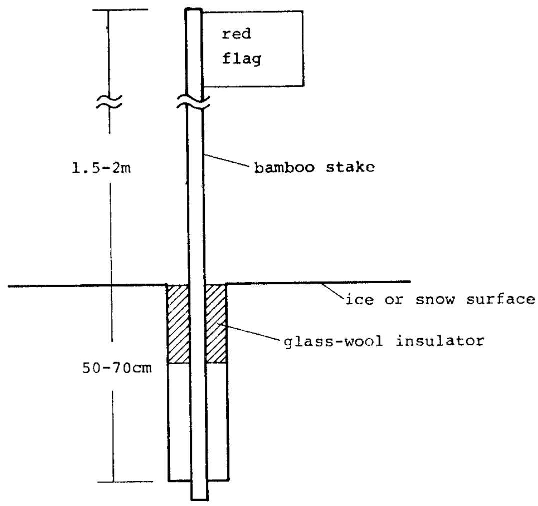

Fig. 3. A schematic illustration of installation of the triangulation marker.

datum point on the exposed rock of the Allan Hills (Station No. 1) and Station No. 20 to the west. The chain is composed of 18 triangles and 20 stations. A strain grid of 650 m×650 m square as shown in Fig. 2 was also installed north of the meteorite concentration area.

Positions and elevations of all the triangulation stations were determined on the basis of the values of the datum point (Station No. 1). The adopted position of this point was 76°42′12″S and 159°31′47″E as obtained from the topographic map of the Convoy Range published by the U.S. Geological Survey. The adopted elevation of 2054 m was obtained by the barometric altimetry in December 1978. A base line, 1546.26 m in length, was established between Station No. 1 and Station No. 2 on the exposed rock of the Allan Hills.

The length of the triangle legs differed considerably from place to place depending on the sighting of a neighboring station. The minimum length was 602.43 m between Station No. 18 and Station No. 19 and the maximum was 2662.70 m between Station No. 16 and Station No. 18.

Bamboo stakes, 2.5 meters long, as markers of triangulation stations, were set into holes drilled in the ice or hard snow surface to a depth of 50 cm to 70 cm. A 3 meter long pole was used to mark Station No. 1 and Station No. 2 as a base line. As illustrated in Fig. 3, these bamboo stakes were wrapped with a glass-wool insulator to keep the stake upright and to prevent melting of the ice or snow by solar radiation.

2.1. Method of survey

The method of survey was based on the standards of the fourth order triangulation of the Geographical Survey Institute of Japan. The survey was conducted principally by angle measurements with Wild T2 theodolites, measuring the horizontal angles of the three or four interior angles of all constituent triangles, and the vertical angles from each station to four or five neighboring stations. All the interior horizontal angles of the 18 triangles were measured with two pairs of observations at the graduated circle readings of 0° and 90°. The limits of error allowed in horizontal angle measurements were 15 seconds as an observed differential, 25 seconds as a double angle difference and 20 seconds as a closure error of a triangle. The vertical angles were measured with one pair of observations, allowing limits of error of 20 seconds as a vertical constant difference.

Distance measurements at Station No. 1–Station No. 2 (base line) and Station No. 19–Station No. 20, were conducted with an optical distance measuring instrument (SDM-1C). The readings were taken several times for a side so that the difference between the values of several measurements was smaller than

$$\pm(0.5+5\times D_m\times 10^{-6})\ \text{cm}$$

where D_m is the measured distance in cm. Air temperature and air pressure were also measured at the same time for distance data correction.

3. Reduction of Observed Data

3.1. Computation of elevation and location

Correction for air temperature and atmospheric pressure was made to the measured distance, but correction due to vapor pressure in the atmosphere was not made since the amount of correction is considered to be negligible at low temperatures.

Slope correction was made with respect to the vertical angle so that the horizontal distance D_h between Station 1 and Station 2 (base line) could be obtained as,

$$D_h=D_m\cos\frac{1}{2}(\alpha_1-\alpha_2) \tag{1}$$

where α_1 is the vertical angle from Station 1 to Station 2 and α_2 is that from Station 2 to Station 1. Both α_1 and α_2 were measured positive in upward direction.

As shown schematically in Fig. 4, i_1 and i_2 are the height of the instrument at Station 1 and Station 2 respectively and f_1, f_2 are the height of the top of the stakes at Station 1 and Station 2. The elevation difference (Δh) between Station 1 and Station 2 was calculated by the following equation;

$$\Delta h=\frac{1}{2}D_h(\tan\alpha_1-\tan\alpha_2)+\frac{1}{2}(i_1+f_1)-\frac{1}{2}(i_2+f_2). \tag{2}$$

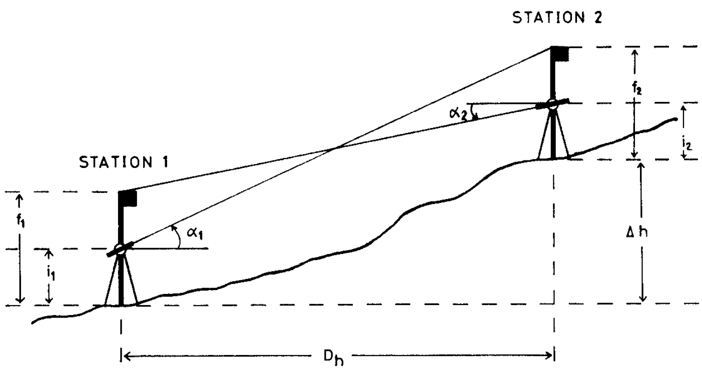

Fig. 4. A schematic figure to measure the elevation difference Δh. The measurement of the vertical angles α_1 and α_2 was made from both Station 1 and Station 2 to each other. Elevation difference can be calculated geometrically by using the values of α, i, f and D_h.

Errors resulting from the refraction by air or the curvature of the earth were counterbalanced by a measurement of the vertical angles from each station. Therefore, the elevation above mean sea level of each triangulation station was obtained by accumulating the elevation differences Δh successively onto the elevation of a preceding station. The elevation of the datum point (Station No. 1) was taken as 2054.00 m.

The horizontal distance between two stations, D_h was subjected to the sea level correction;

$$D_e = D_h(1 - \bar{H}/R) \tag{3}$$

where D_e is the distance at sea level, $\bar{H}$ the mean sea level elevation of two stations, and R the radius of the earth's curvature.

Positions of all triangulation stations were calculated by the observed data and by means of net adjustment. At each station the computation of net adjustment was made by the least square method from the observation equations, whose unknown factors was the correction term to approximate values of (X, Y) coordinates of an unknown station.

3.2. *Results of computation*

The latitude, longitude, elevation H and cartesian coordinates (X, Y) of all stations are tabulated in Table 1, where it is taken as H=2054.00 m, X=0.000 m, Y=0.000 m at the datum point (Station No. 1). The direction of X coordinate is geographical north and that of Y is east. Standard error of coordinates, M_x and M_y, and elevation, M_h, were also tabulated in Table 1.

The error in position of the farthest station (No. 20) from the datum point

Table 1. Positions, elevations and (X, Y) coordinates of all stations of a triangulation chain. Standard errors of (X, Y) coordinates, M_x and M_y, and errors in elevation, M_h, are also tabulated.

Station	Latitude (S)	Longitude (E)	Elevation (m)	M_h (m)	X (m)	Y (m)	M_x (m)	M_y (m)
1	76°42′ 12″.000	159°31′ 47″.000	2 054.00		0.000	0.000		
2	76 41 23.045	159 32 28.317	1 909.86	0.026	1 517.688	295.009	0.063	0.056
3	76 41 22.566	159 30 20.442	1 945.69	0.022	1 532.451	−618.038	0.076	0.091
4	76 41 44.891	159 29 35.849	1 955.71	0.022	840.165	−936.010	0.078	0.070
5	76 41 25.707	159 29 18.743	1 952.81	0.023	1 434.834	−1 058.505	0.086	0.094
6	76 41 51.525	159 27 14.905	1 954.14	0.027	633.532	−1 941.642	0.135	0.142
7	76 41 28.543	159 27 50.035	1 951.79	0.026	1 346.326	−1 691.757	0.114	0.138
8	76 41 40.388	159 24 18.041	1 946.67	0.032	976.667	−3 204.461	0.203	0.265
9	76 42 09.539	159 26 13.322	1 949.42	0.031	74.424	−2 380.215	0.192	0.184
10	76 42 21.393	159 21 51.547	1 945.19	0.040	−297.182	−4 246.491	0.313	0.391
11	76 41 54.137	159 20 21.454	1 944.51	0.042	545.876	−4 891.719	0.325	0.453
12	76 42 48.483	159 18 24.811	2 030.50	0.046	−1 141.894	−5 717.646	0.456	0.561
13	76 42 01.624	159 18 07.166	2 008.37	0.046	310.358	−5 849.034	0.399	0.560
14	76 42 06.975	159 16 32.599	2 014.37	0.047	141.714	−6 522.993	0.453	0.638
15	76 42 45.665	159 15 12.369	2 046.54	0.051	−1 060.335	−7 089.690	0.539	0.713
16	76 41 50.192	159 11 20.176	2 022.05	0.060	650.776	−8 754.696	0.634	0.872
17	76 42 51.058	159 09 08.586	2 075.30	0.065	−1 241.910	−9 681.620	0.740	0.988
18	76 42 25.604	159 05 40.232	2 067.58	0.068	−463.060	−11 172.404	0.853	1.118
19	76 42 44.773	159 05 26.531	2 075.06	0.068	−1 058.041	−11 265.666	0.865	1.129
20	76 42 20.517	159 03 35.989	2 070.81	0.070	−312.144	−12 059.605	0.932	1.128

is ±0.932 m in X coordinate and ±1.128 m in Y coordinate.

Errors in elevation were calculated in accordance with the law of propagation of error; the maximum error is ±7 cm at Station No. 20.

The standard error of unit weight in the angle measurement is 7.40″.

4. Characteristic Features of the Allan Hills Bare Ice Field

It has been observed by NARUSE (1978) that the bare ice in the Meteorite Ice Field near the Yamato Mountains is moving upwards with a velocity of about 5 cm/year. The upward motion of the bare ice mass is caused by the obstruction effect of the bedrock topography. The bedrock surface is not horizontal flat at all but has a complicated topography which forms a barrier obstructing the flow of the ice sheet.

DREWRY (1979) conducted a systematic airborne radio echo sounding of the surface and bedrock topography inland of the McMurdo Sound region and in South Victoria Land. He prepared a contour map of the sub-ice bedrock at 200 m intervals, showing the continuation of mountains topography declining westwards from the Transantarctic Mountains.

On the basis of the contour map of sub-ice bedrock and the bare ice area

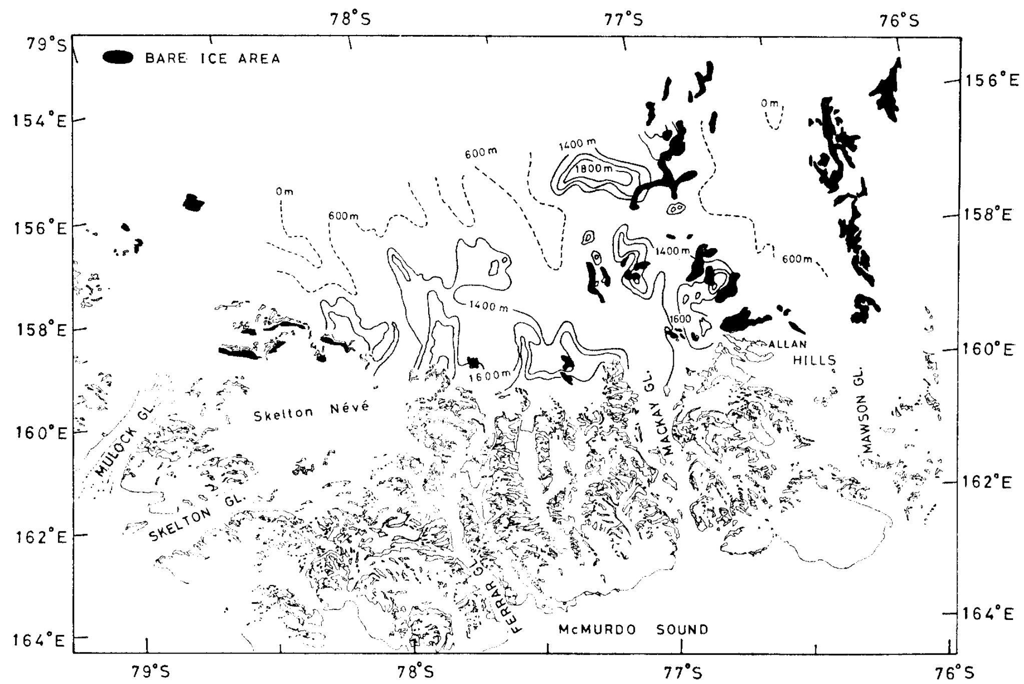

Fig. 5. Bedrock configuration inland of the McMurdo Sound from radio echo sounding (after DREWRY, 1979), and the distribution of the bare ice area identified, deciphered from the ERTS-1 satellite imagery.

on the ice sheet surface identified from the ERTS-1 imagery, the configuration of the bedrock surface topography and the distribution of the bare ice area are shown in Fig. 5. The dark areas show the bare ice fields on the ice sheet surface; the sub-ice bedrock surface elevation is depicted by the contour line of 0 m and 600 m (dotted line), and 200 m intervals higher than 1400 m (solid line). As shown in the figure, the extensive bare ice area on the ice sheet surface in the vicinity of the Allan Hills is existing in the upstream of the mountain range, and the bare ice fields inland west to the plateau of the East Antarctic ice sheet along 77°S in latitude are located in the neighborhood of a sub-ice bedrock mountain. The flow lines of the ice sheet surface have been constructed from the surface contour map of DREWRY. The surface contour map suggests that the ice sheet flows from the southwest to the northeast towards the Mawson Glacier. The ice sheet flow coming down towards the Allan Hills or into the Mawson Glacier is prevented from flowing in the bare ice areas by the mountain range or the sub-ice mountains. Therefore, the ice flow coming down towards the Allan Hills or into the Mawson Glacier should be forced to make an upward movement in the neighborhood of the mountains.

Fig. 6 is an enlarged illustration of Fig. 5, showing the bare ice area in which a large number of meteorites were collected and the triangulation stations

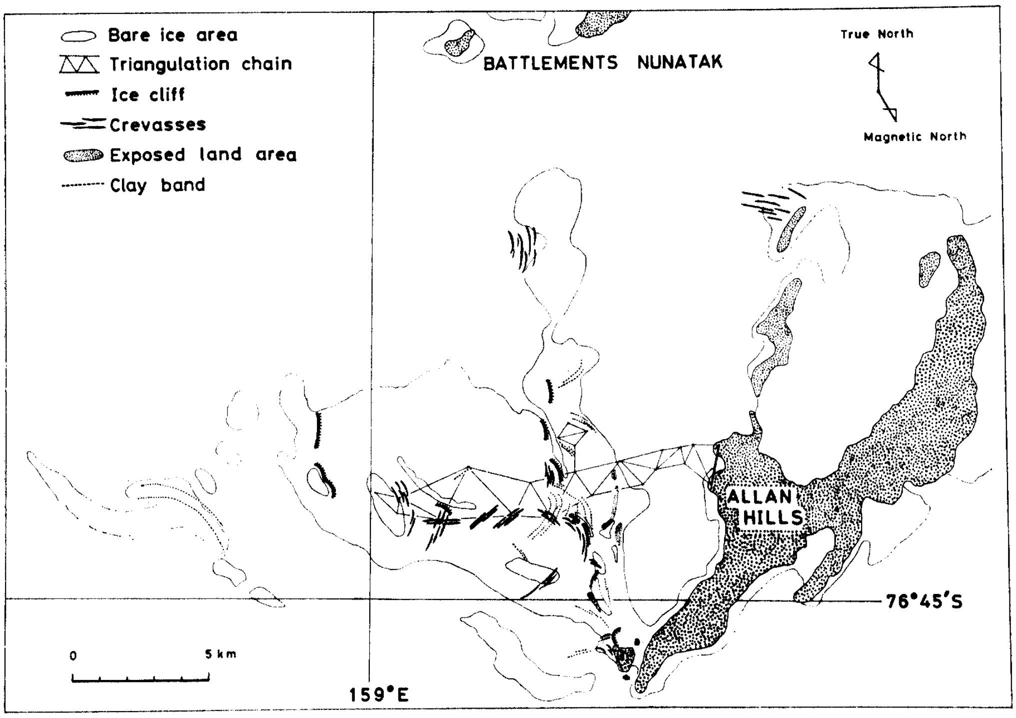

Fig. 6. Surface morphology and location of the triangulation chain in the Allan Hills bare ice field.

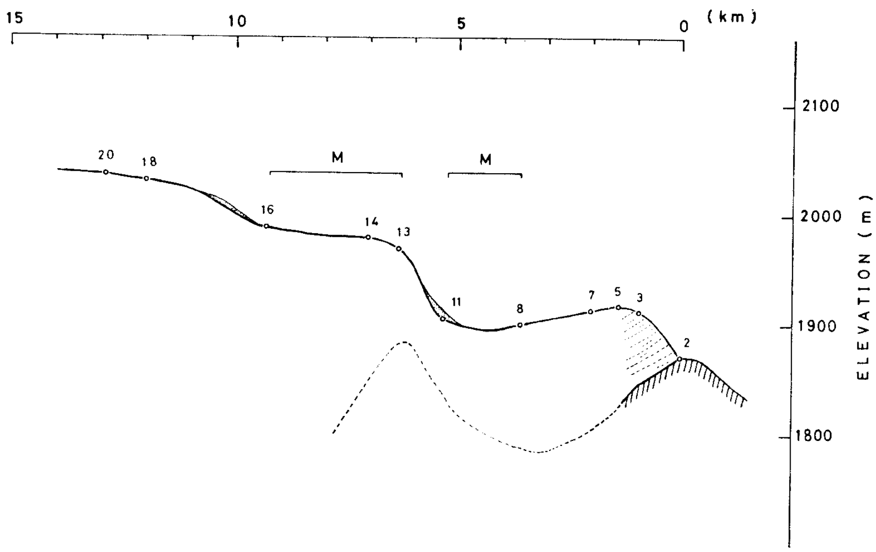

Fig. 7. Vertical profile of the ice sheet along the triangulation chain.

of the glaciological survey are located. The ice cliffs extend north towards the Battlements Nunatak from the southwest end of the Allan Hills and the crevasse patterns suggest that the ice sheet surface flow may be from the southwest to the northeast.

Fig. 7 shows the vertical profile of the ice sheet along the triangulation Stations 2, 3, 5, 7, 8, 11, 13, 14, 16, 18 and 20. The dotted areas at Station 11 and Station 16 show the firn snow deposited on the bare ice surface beneath the ice cliff. Letter M marks the location of the meteorite finds collected on the bare ice surface. The surface topography of the Allan Hills bare ice field is characterized by a step-like ice sheet surface, which might be considered to reflect the effect of the sub-ice bedrock topography upon the ice sheet flow. Therefore, it is important not only to resurvey the triangulation chain but also to carry out more detailed radio echo sounding on the bare ice area.

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